Integration of ecosystem science into radioecology: a consensus perspective

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ABSTRACT

In the Fall of 2016 a workshop was held which brought together over 50 scientists from the ecological and radiological fields to discuss feasibility and challenges of reintegrating ecosystem science into radioecology. There is a growing desire to incorporate attributes of ecosystem science into radiological risk assessment and radioecological research more generally, fueled by recent advances in quantification of emergent ecosystem attributes and the desire to accurately reflect impacts of radiological stressors upon ecosystem function. This paper is a synthesis of the discussions and consensus of the workshop participant's responses to three primary questions, which were: 1) How can ecosystem science support radiological risk assessment? 2) What ecosystem level endpoints potentially could be used for radiological risk assessment? and 3) What inference strategies and associated methods would be most appropriate to assess the effects of radionuclides on ecosystem structure and function? The consensus of the participants was that ecosystem can and should support radiological risk assessment through the incorporation of quantitative metrics that reflect ecosystem functions which are sensitive to radiological contaminants. The participants also agreed that many such endpoints exit or are thought to exit and while many are used in ecological risk assessment currently, additional data need to be collected that link the causal mechanisms of radiological exposure to these endpoints. Finally, the participants agreed that radiological risk assessments must be designed and informed by rigorous statistical frameworks capable of revealing the causal inference tying radiological exposure to the endpoints selected for measurement.

1. INTRODUCTION

This manuscript presents the findings of a workshop designed to promote a stronger integration of the ecological sciences within the discipline of radioecology. The goal of the workshop was to bring together participants from a variety of disciplines in ecosystem science and radioecology to evaluate the rationale, benefits, and obstacles of integrating more ecological methods into the field of radioecology (*Integrating Ecosystem Research into Radioecology in the Nuclear Age;* Aiken, South Carolina, October 3 - 5, 2016). A discipline-wide strategic research agenda in radioecology has also expressed the need to integrate ecosystem approaches into radioecology (Hinton et al. 2013).

Some readers might logically ask: "Why is the discipline of 'radioecology' striving to find ways to integrate with the broader discipline of ecology?" The answer requires an understanding of how radioecology developed, and the long-standing anthropocentric view taken by international organizations responsible for environmental radiation safety. A bit of that history is appropriate as an introduction to this manuscript. For brevity, and because of its early dominance in nuclear weapons testing, the historical connections between ecology and early radioecology is presented largely from a United States perspective. A similar history was unfolding in Russia and other nuclearized countries such as France and Canada during the same period.

Radioecology emerged as a scientific discipline at the end of World War II, in response to environmental problems from radioactive fallout associated with nuclear weapons testing Driven by the need to understand environmental issues of radiation, a 'golden age' of funding developed between 1950 and 1965 for radioecology (Hagen 1992). During this period, radioecological research produced new knowledge about the environmental transfer of radionuclides through agricultural systems and the uptake of radionuclides by biota. Ecologists embraced the sub-discipline of radioecology because of the available funding, and because radioisotopes proved to be incredibly powerful tools when used as tracers of environmental processes in field studies. Some historians of environmental sciences claim that the beginnings to the Age of Ecology were due in part, and occurred concurrently, to problems associated with the Atomic Age (Worster 1994). This viewpoint is supported by the fact that with the advent of radioisotope tracers, ecologists, for the first time, had a tool that allowed them to quantifythe rate of material and energy flow through ecosystems. Ecologists Eugene and Howard Odum were at the forefront of this science in the U.S. In Russia, also a dominant early tester of nuclear weapons, Vladimir Vernadsky pioneered the science through his experiments on the uptake of natural radionuclides by aquatic plants in 1929 (see: http://www.iur-uir.org/en/awards). Both countries saw rich, long-standing contributions to radioecology during the early periods of nuclear weapons development.

By the late 1960s, however, the primary funding agencies were no longer interested in supporting large-scale, field research on radiation. Priorities shifted away from radioecology and funding for its research dropped precipitously. Additionally, expanding safety regulations limited ecologists' use of radiotracers in the field, and most ecologists moved to other areas of ecological research. Radioecology became very applied, with an emphasis on human radiation safety and the development of associated environmental transport models based largely on simplified empirical ratios. The environment was recognized, but only as a pathway to human exposure. Research on the effects to the environment were seldom funded, and the ecology in radioecology began to slip away. Funding agencies did not see a need for environmental radiation effects research because international agencies responsible for radiation safety believed that if man was adequately protected, then so was the environment (ICRP 1977; ICRP 1991; UNSCEAR 1996).

The extreme anthropocentric view was criticized sufficiently that in 2005 the International Commission on Radiological Protection (ICRP) formed Committee 5 to address environmental radiation safety more directly. The “Reference Animals and Plants (RAPs)” approach developed by Committee 5 to evaluate environmental risk took much inspiration from the European ERICA project which evolved more or less at the same time (Larsson 2007; Prlic et al 2017). Based upon the development of quite similar approaches, they are viewed by many as a good start, but one lacking ecological methods to examine effects at higher levels of biological organization (Bréchignac 2012; Bradshaw et al. 2014). One major shortcoming arises from the important gap between the stated objectives of radiation protection of the environment which are consensual (protecting biodiversity, ecosystems, etc…) and the method proposed to achieve them which is largely based upon dose-effects relationships at individual organism level. Whilst some efforts have been initiated under the IAEA MODARIA program to promote modelling of radiation effects from organisms up to populations (Sazykina and Kryshev 2016; Alonzo et al 2016), Committee 5 was abolished by the ICRP in 2017. Although radiological protection has been slowly broadening from a system focused solely on human radiological impacts to one that encompasses non-human biota and the environment itself, there remains a distinct deficit in ecological expertise within the field. Arguably, radioecology has now lost many of its practicing ecologists with state-of-the-art knowledge.

Recognizing the problem, the International Union of Radioecology (IUR) convened an international symposium to assess the status of current radioecology research (Bréchignac 2016; Bréchignac et al. 2016). A critical issue noted during discussions at the symposium was the paucity of ecosystem scientists now working within the field of radioecology. Consequently, there is limited expertise within the field of radioecology to address the utility and feasibility of incorporating ecosystem level metrics into radiological risk assessments and radiation protection programs.

This gap in expertise was the catalyst for the idea to bring radioecologists and ecosystem ecologists together for in depth discussions of how feasible the integration of ecosystem approaches into the field of radioecology would be, given the current state of our knowledge in both subdisciplines of ecology, and to develop a consensus around the justification and rationale for integration of ecosystem science into the field of radioecology. To develop such a consensus, the authors felt that three primary questions must be addressed: 1) How can ecosystem science support ecological risk assessment? 2) What ecosystem level endpoints potentially could be used for radiological risk assessment? and 3) What inference strategies and associated methods would be most appropriate to assess the effects of radionuclides on ecosystem structure and function? These questions were posed to workshop participants who engaged in discussions over a three-day period to develop consensus viewpoints and a framework for improved integration of ecosystem science into future radioecological research.

2. METHODS

The workshop *Integrating Ecosystem Research into Radioecology in the Nuclear Age* was held in Aiken, South Carolina USA from October 3 - 5, 2016. Participants were invited from the memberships of the Association of Ecosystem Research Centers (AERC) and The International Union of Radioecology (IUR), and the scientific staff of the Savannah River Ecology Laboratory (SREL), as well as from a set of radioecologists, ecosystem ecologists, and ecological risk assessment professionals from the US, Europe, and Asia selected to provide a broad set of disciplinary perspectives to address the workshop goals. A total of 60 scientists from academia, government and private industry participated in the workshop (See Table 1 for a complete list of participants and their affiliations).

Day one of the workshop was initiated with a set of specifically-targeted, invited presentations, designed to provide workshop participants with some background in relevant topics such as radioecology, ecosystem science, ecological risk assessment, and statistical inference (Table 2). On Day two, participants were assigned into six groups (with 9-10 members in each group, each representing a mixture of the disciplines represented) to discuss and respond to each of three separate question sets (provided in results below). By the end of day two, notes from each of the six groups were compiled for each of the three questions and redistributed to all workshop participants for review and consideration.

On day three, participants were reassigned to each of three synthesis groups and each synthesis group was assigned to develop consensus responses to one of the three question sets that were evaluated on day two. Each synthesis group was able to utilize the compiled responses of the six breakout groups for their assigned question set as a starting point for developing their consensus responses. Each of the three synthesis groups was led by one of the workshop organizers to ensure that a consensus response was created and recorded for each question set.

3. RESULTS

To address the primary questions of the workshop, clear definitions of terminology are needed. Therefore, key concept definitions are compiled in a Glossary at the end of this paper.

3.1. Question 1: *How can ecosystem science support ecological risk assessment?*

3.1.1. Are ecosystem level endpoints currently used in ecological risk assessment in any form?

There was a wide consensus among workshop participants that ecosystem-level endpoints are already used in ecological risk assessments.

Several examples of ecosystem-level endpoints currently in use include: invertebrate bioindicators (Hodkinson and Jackson 2005; Gerlach et al. 2013; Kilgour et al. 2018); use of indices of "biotic integrity", "ecological integrity" or "environmental status" to measure effects of water quality on ecosystems (Toham and Teugels 1999; Borja et al. 2008; Kane et al. 2009); and use of dissolved oxygen status which can be viewed as an ecosystem-level endpoint related to eutrophication (Liu et al. 2015). These are but a few examples within the literature demonstrating that ecosystem-level ecological risk assessments are possible and already carried out under a variety of conditions (Munns Jr et al. 2016).

Although not yet widespread in risk assessment practice, it must be stressed that other features of ecosystems could be used as endpoints (USEPA 2015). Among these, the quantification of indicator species and keystone species are good examples of other ecosystem endpoints that can be used to assess risk. Indicator species are species that are present in well-functioning ecosystems, but absent or depleted in impaired ecosystems. Keystone species are species whose presence is necessary for the operation of key functional processes (Jordan 2009). These concepts are well-developed in the ecological literature, and could be more widely used in risk assessments. In addition, methods for ecosystem network analysis, a concept that is currently evolving in ecology (Lau et al. 2017), could also be useful for deriving ecosystem endpoints for risk assessment. For example, endpoints responding to ecosystem stress such as local node connectivity, node density at each trophic level, link density, nestedness, or richness could be used as metrics for risk assessment at the ecosystem scale (Ulanowicz 2004; Tomczak et al. 2013; Gray et al. 2014; Lau et al. 2017).

In contrast to traditional risk assessments, which often focus on organism-level traits as endpoints (e.g., physiological, reproductive, or genetic attributes of individual organisms), temporal and spatial scales are essential components to be considered at the ecosystem level in ecological risk assessment. Obviously, the spatial scale of the assessment would depend upon the ecosystem or organisms in question. For example, the time scale employed would need to be much longer if trees were included (i.e., at least as long as the life span of a tree) than if the focal system was soil microbes. If population viability is part of an assessment, time scales spanning a number of successive generations would need to be used. Quite similarly, the spatial extent of an assessment would also need to reflect the size of the ecosystem in question. The importance of time and space considerations when assessing ecosystem endpoints, challenges the use of the conventional dose-response concept (developed for organisms) that is typically used to assess exposure to radiation, as we currently do not know how to define or measure a relevant "dose" to an ecosystem. Contaminated landscapes are often characterized by heterogeneous concentrations of radionuclides, which translate to heterogeneous doses of radiation to organisms and their populations. This also implies that estimating or mimicking the effects of an average dose would not be a meaningful way to estimate risk. Similarly, time scales corresponding to a significant number of generations, presumably representative of a population's viability, would probably better be related to dose in terms of "accumulated dose" than in terms of "dose rate", thereby challenging typical methodology employed to estimate risk.

3.1.2. Are extrapolations from organismal health to ecosystem health possible, justifiable and scalable?

In risk assessments, extrapolations are widely used for the sake of ease and practical application of risk calculation methods. This approach is justified when the validity of extrapolations has been demonstrated and the associated uncertainties established. However, extrapolations also are often used to overcome limited scientific understanding, without real validation, leading to uncertainties which weaken the robustness of the conclusions drawn. Discussion of extrapolation issues is therefore paramount in risk assessment (Munns Jr et al. 2016).

For example, organismal health is but one of many determinants of ecosystem condition. Therefore, extrapolating from the organism to demonstrate the health of the ecosystem may not be an effective approach. Unfortunately, current regulatory assessments of exposure to radiation are most often focused on organism-specific responses. If single organism assessments are to be used to assess ecosystem condition, then it will be important to ensure that keystone, indicator, or sentinel species are the focus of these assessments. However, to establish more broadly applicable assessment approaches across a range of ecosystem types it may be necessary to identify alternative measures of ecosystem condition, such as energetics or services endpoints. Achieving this would require research that informs the establishment of dose (or more realistically media activity concentration)-response relationship at these higher ecosystem levels. Such research should allow the development of appropriate modeling techniques, which require a minimum set of parameters to be measured or predicted for the purposes of ecosystem impact assessment. The result of this assessment should be a quantification of ecosystem impact with a given degree of confidence. Current experimental work to establish dose-effect relationships is focused mainly at the single organism and micro/mesocosm scale, but it would be necessary to establish the relationship between experiments at these scales and ecosystem condition.

To characterize the status of an ecosystem it is necessary to establish relevant endpoints; these may include:

Metrics from community ecology such as keystone (sentinel) species -- If a keystone species approach is used, then it is to be accepted that the keystone species is an appropriate way to assess the status of an ecosystem (the point here is that the large uncertainty associated with such an approach is accepted and that multiple keystone species from different trophic levels would be required to represent an ecosystem) and so it is appropriate to extrapolate organismal health as an indication of ecosystem condition. The concept of resource availability and carrying capacity as metrics of ecosystem condition also might be appropriate (Zhang et al. 2020). Additionally, biodiversity measures might be appropriate in that such estimates are likely indicative of ecosystem stability in wake of disturbance (Pennekamp et al. 2018).

Metrics tied to the energy flow through ecosystems [decomposition, biomass production, etc.] -- If looking at energetics as an indicator of ecosystem condition (Schlichting et al. 2019), the focus no longer lies on organismal health and there will be a need to develop some sort of a dose response relationship for the energetics of individual ecosystems.

Metrics derived from analyses of ecosystem networks -- If considering connectedness, link density (obviously related also to biodiversity) or other metrics as indicators of ecosystem condition derived from ecosystem network analysis, there would be a need to develop a dose response relationship for the nodes connection richness of an ecosystem. In addition, mobility of species within each focal network would be an important parameter if such metrics were to be employed.

Metrics tied to the quality and stability of ecosystem services – If using ecosystem services as an endpoint, it would be necessary to develop dose response relationships for service delivery (water quality, air quality, erosion control, nutrient cycling, biodiversity, etc.). This raises the question of whether a single dose response relationship is appropriate or a range of dose response relationships for different services. Regardless, it is likely that ecosystem specific dose response relationships would need to be developed, at least for some ecosystem services.

It is important to note that there is one domain of ecological risk assessment that has achieved scientific maturity, nutrient loads are well known to be critical for ecological risk assessment of the eutrophication process in aquatic ecosystems (van Liere et al. 2007; Liu et al. 2015). This example demonstrates the pertinence and the promising prospects of promoting further research in this direction. Alternatively, one should also consider the vulnerability of ecosystems (De Lange et al. 2010), as the counterpart of resilience which includes recovery ability/time after perturbation. It may be possible to discuss resilience in terms of "levels of disaster," which are defined by the time required for ecosystem recovery.

Ultimately, justification for moving to an ecosystem level approach for regulation would require that it be pragmatic and economically and technically feasible. This means that in an ecosystem approach, endpoints will need to be accepted by a wide range of stakeholders, which would provide for the inclusion of stakeholder values in the decision making processes. In addition, to successfully incorporate ecosystem level endpoints into environmental risk assessment, there is a need to establish accurate dose response relationships at low dose and chronic low dose environmental exposure situations. Experimental relationships based on LD_{50}s from high dose experiments do not necessarily capture the dose response for low doses. These relationships will need to be more clearly defined in order to build validated models for both organisms and ecosystems. To develop a relevant dose response relationship for ecosystems, it may be important to focus on attributes which can be accurately measured and modelled, such as ecosystem energetics (biomass and decomposition measurements) or nodes of interconnectedness.

3.1.3. Should we account for ecosystem resilience in ecological risk assessment, and how?

There is ample empirical evidence that the resilience of an ecosystem to perturbations is linked to biodiversity, and this offers a potential for developing alternative metrics that could support risk assessments (Oliver, Heard, et al. 2015; Oliver, Isaac, et al. 2015). However, among participants of the workshop, there was wide consensus (although not complete, i.e., five of the six groups) that whereas metrics of ecosystem resilience could be significant for ecological risk assessment, current definitions (see glossary) associated with resilience and methods used to quantify resilience are still too limited to allow for a wide operational use of this concept. This concern was the argument that the dissenting group used to reject the idea that resilience could be used as a method for risk assessment. Resilience is therefore an important concept, but ecosystem scientists need to do much more research to develop methods for identifying critical transition points in ecosystems prior to the occurrence of catastrophic changes. A review of evidence for ecological thresholds using case studies has been recently performed by Sasaki et al. (2015) and may be useful to apply to this task.

3.1.4. Are there direct, quantifiable ties between organismal health and ecosystem integrity?

The group discussions resulted in a modification of the wording of the question from ecosystem condition to ecosystem integrity as presented above. The group acknowledged that while there are likely both direct and quantifiable ties between organismal health and ecosystem integrity, more information is needed to link functional relationships between organisms, specific ecosystem processes, and the characteristics that determine ecosystem integrity. In this context, three main issues were identified as being critical to understanding the nature of functional relationships between organisms and ecosystem processes. The first issue relates to the variance in magnitude of these functional relationships across organisms or organismal groups. For example, some ecosystems have apex predators or other keystone species that disproportionately influence ecosystem function. In systems that depend on a few keystone species, controls over ecosystem function can be either top down or bottom up, and links to ecosystem processes may be more easily quantified; examples of such quantifiable links would include changes in abundance of dominant plant species, critical link species (such as pollinators), dominant herbivores and/or predators, or invasive species.

The second issue acknowledges that although health of individuals may be compromised, only population level impacts will affect ecosystems. An individual organism is ecologically insignificant unless placed in the context of a population because the population, rather than the individual, will impact an ecosystem through time (Bréchignac 2012).

The third issue recognizes that while both structural and functional attributes of ecosystems are important to ecosystem function, additional work needs to be done to elucidate the context and rates at which changes at the organismal level scale to those observable at the ecosystem level (Munns Jr et al. 2009). There is a need for quantitative data concerning changes to the ecosystem structure resulting from radiation exposure, such as changes in the productivity of a population or predation patterns governing species interactions. It is important to recognize in this context that sublethal effects may be as (or even more) important as (than) outright mortality when attempting to scale the impacts of radiation on individuals to ecosystems. For example, behavioural changes, reduced reproductive success, reduction of food resources, increased disease susceptibility or changes in phenology of populations or communities could impact ecosystem structure in unexpected ways. Similarly, secondary effects, such as changes in leaf chemistry, are critical to consider as they might decrease food quality or acceptability for consumers such as microbes or invertebrates.

When attempting to assess ecosystem integrity it is important to identify indicator species to ensure that they respond to the specific stressor of interest in a way that explicitly links species characteristics to ecosystem condition. It is also important to quantify integrity of the ecosystem using high resolution data obtained from measurements including, but not limited to eDNA and DNA barcoding, water color, or Normalized Difference Vegetation Index (NDVI), in conjunction with environmental variables and taxa specific measurements which may vary in difficulty and complexity.

Question 2

3.2. What ecosystem level endpoints potentially could be used for radiological risk assessment?

3.2.1. What advantages may there be to using ecosystem endpoints associated with radiological stressors in ecological risk assessment?

Participants agreed that endpoints measured at the level of the ecosystem (such as biomass production, decomposition, nutrient cycling, biodiversity, and carbon dynamics) can be useful for a wide variety of reasons and they represent a potential shift away from the recognized short-comings associated with the ICRP's reference and animal and plant approach (ICRP 2008). Recognizing this shortcoming, the IAEA MODARIA program sought to promote modelling of radiation effects from organisms up to populations (Sazykina and Kryshev 2016; Alonzo et al 2016), however this effort has been largely theoretical and Committee 5 of the IAEA has been discontinued. The group also recognized that ecosystem endpoints could provide a more holistic assessment of ecosystem condition than is the case for endpoints measured at the level of the individual organism and thus, interaction and confounding variables might interfere less in risk analyses performed using such endpoints. In addition, because ecosystem level endpoints integrate across space and time, they may be more stable and reliable than endpoints measured at lower levels of biological organization (e.g., organism or population levels) and might allow risks from multiple stressors to be assessed simultaneously (Nienstedt et al. 2012).

The group also recognized that measurements at lower levels of biological organization (below the ecosystem level) remain important to risk analyses, depending on the scope and goals of the assessment. Thus, some disadvantages of using ecosystem measurement endpoints exist, primarily because we may not have sufficient knowledge of, or experience with, ecosystem endpoints to know if levels of change detected in such endpoints are biologically significant and truly attributable to the stressors of interest (Forbes and Calow 2012). It is also unknown if quantifiable ecosystem endpoints are as sensitive to radiation stress as are organism-based metrics. Finally, the time required to quantify ecosystem level endpoints could be prohibitive for risk assessments and subsequent licensing processes, making effect indicators at lower levels of biological organization perhaps better choices for early warning signs of risk.

3.2.2. What ecosystem attributes would be expected to reflect responses to radionuclide stressors, and; are there ecosystem responses that would be expected to be unique to stressors such as radionuclides vs other potential contaminants?

The response from any stressor, including radiation, is dose dependent. If radiation doses are sufficiently high, alterations to ecosystem attributes will occur. Though experimental tests of high doses of radiation are understandably limited, we do have some indication of how ecosystems respond to this type of stressor (e.g., Puerto Rico (Odum and Pigeon 1970); Canada (Amiro and Sheppard 1994); and Russia (Alexakhin et al. 1994)). Extremely high exposures also occurred during the first month after the Chernobyl accident, when dose rates were sufficient to kill the adjacent pine forest and species-dependent radiosensitivity and ecosystem-level effects were evident (Hinton et al. 2007). Such examples are atypical. They are not the conditions under which an ecological risk assessment would be conducted, but they are ideal field sites to conduct ecosystem-response research as they provide the opportunity to quantify ecosystem responses to radiation as a significant source of environmental stress (Beresford et al. 2020).

Under more typical radiation release scenarios, and even with the elevated releases from the Fukushima Daiichi Nuclear Power Plant, the group was not aware of any data that clearly indicate a direct impact of radiation on any ecosystem-level process (although subsequent to this workshop at least one paper has addressed this issue (Bonzom et al. 2016)). This is not to say that ecosystem-levels processes have never been studied in radioactively contaminated areas. For example, Møller et al. (2012) recorded a lower abundance of pollinating insects in more contaminated sites within the Chernobyl Exclusion Zone, seemingly translating into lower productivity (i.e., lower fruit production and recruitment of fruit trees). However, no attempt was made to estimate the dose received by the pollinating insects nor the plants. Such evidence remains inconclusive as to whether such is due to direct radiation exposure, or rather to indirect, ecological changes. Nonetheless, radiation is relatively easy to detect compared to many other types of contaminants. For gamma-emitting radioisotopes it can often be done external to animals, plants, or abiotic features and assayed non-destructively. In addition, recent advances in GPS-dosimetry (e.g. Hinton et al. 2015; Aramrun et al. 2018; Aramrun et al. 2019) allow the spatial and temporal variation in radiation exposure to be quantified on free-ranging wildlife, which can also provide indirect data on exposure levels at fine scales within the ecosystem of interest. This is not possible with most other types of contaminants.

Radiation does have properties that might cause an environment to respond differently than if exposed to some other type of stressor. For example, radioisotopes could potentially be damaging as both a chemical stressor and a radiation stressor. Uranium isotopes are known to be chemically damaging to the kidneys, and if inhaled their alpha emissions could damage sensitive lung tissues. In addition, some types of physiological damage may be unique to radiation. Dicentric formation in damaged chromosomes, a type of reciprocal translocation, are the standard for radiation biodosimetry in humans (Liu et al. 2017) , and likely pertinent to wildlife as well. Radioactive decay also is a unique process among environmental contaminants and reduces the concentration of radiation over time. The loss of contaminant concentration due to radioactive decay might allow an ecosystem to recover more quickly than stable, persistent contaminants such as heavy metals. Furthermore, external irradiation is an additional pathway of exposure that is unique to radiation and may be greater (Kubota et al. 2015) or equal to internal exposure rates depending upon the environment (e.g., terrestrial vs marine) and concentration factor for specific radionuclides in each environment (Vives I Batlle et al. 2014).

There are several other aspects of radiation that are exclusive to this form of contamination. For example, when considering external irradiation, bystander effects and genomic instability are phenomena that may be unique to radiation as a contaminant. Their relevance is that they both initiate the response of cells and organisms to low doses and dose rates and are thought to persist for several generations in both cells and organisms (Mothersill and Seymour 2000; Smith et al. 2016; Smith et al. 2018). Radio adaptation to chronic low level exposures to radioactivity has been observed at Chernobyl (Rodgers and Holmes 2008) and bystander effects which influence signalling mechanisms and enhance genomic instability can result in persistent higher than expected tolerance of the system for mutations (Mothersill and

Seymour 2012; Mothersill et al. 2018). Although they may be unique to radiation, they are not currently factored into radiation protection risk analysis mainly because of uncertainty about what the effects mean. Finally, the impacts of radioactive contamination may also be confounded because human radiation safety regulations require humans to be evacuated from contaminated sites at radiation levels that permit wildlife to remain. The exclusion of humans from large areas such as Chernobyl and Fukushima may cause changes in some ecological endpoints (e.g., biomass production, species diversity) that are greater than those caused by the radiation stressor (Deryabina et al. 2015; Webster et al. 2016). Human exclusion from large areas and the confounding effect of their absence may not occur in response to other stressors (Lyons et al. 2020).

The group also recognized that cosmic generated and terrestrial background radiation have existed since Earth's formation. All organisms have evolved to counter radiation stress. For example, burrowing animals that are exposed to high doses from naturally emitted radon seem to cope very well with these exposures (Macdonald and Laverock 1998). Radiation causes indirect damage at the cellular level due to ionization of water and the formation of destructive free radicals. Natural metabolism also causes free radical damage. All organisms have evolved DNA repair mechanisms to counter the damage from metabolic by products, although the efficiency of these repair mechanisms vary across taxa and tissues within individual organisms. The same repair mechanisms are activated if the organism is stressed from radioactive contamination. The existence of an 'on-board, ready repair tool kit' makes coping with radiation exposures potentially less stressful than exposure to evolutionarily more recent contaminants, (such as organics, endocrine disruptors, etc.) for which organisms have not had time to evolve as effective repair processes. Of additional importance is hormesis, which is a positive, protective response to some radiation exposures. Exposures to low doses of radiation can activate repair mechanisms, which in turn protect the organism from additional, higher level exposures (Baldwin and Grantham 2015).

3.2.3. Can individual and/or population level endpoints be tied to the quantifiable ecosystem endpoints identified above for radionuclides?

The group consensus to this question was: Yes, in theory, but it is critical to understand the linkages within the ecosystem. The group was not aware of any solid empirical data linking radiation effects at the individual or population levels to quantifiable ecosystem endpoints.

Additionally, such linkages have not been solidified in the general field of ecology for other types of contaminants. Barnthouse (this workshop) stated that field studies of chemical pollutants usually focus on measuring exposure or tissue concentrations which are extrapolated to the population level, rarely are emergent population or ecosystem characteristics the focus of measurement.

This workshop has revealed to radioecologists in the group that their science may not be so far behind general ecological risk analyses being conducted for other stressors (e.g., see van Straalen and van Gestel 2008; Liess and Beketov 2011). Many of the same problems that are in need of solving in radiological risk assessments are still dominant in the risk assessments of other contaminants. This includes the difficulty of linking effects of stressors to various levels of biological organization.

<u>Question 3</u>

3.3. What inference strategies and associated methods would be most appropriate to assess the effects of radionuclides on ecosystem structure and function?

3.3.2. What role can statistical inference play in evaluation of ecosystem level endpoints of potential value to risk assessment associated with radionuclide exposure?

The group strongly agreed that statistics are needed to produce defensible risk assessments and should be a central element of the environmental risk assessment process. The use of statistical frameworks allows us to break away from more ritualistic, subjective approaches that are used far too often in current risk assessment frameworks. It is imperative that the choice of statistical methods be well fitted to the type of data available and scope of the questions being asked (e.g., hypothesis testing vs methods such as Bayesian belief networks). While we acknowledge that there are special cases when risk assessments involving radiological materials may require the use of qualitative data, use of these types of data should be minimized to avoid situations where “expert judgement” or “weight of evidence” approaches serve as the central underpinnings for risk assessments. By definition, risk assessments determine the probability of a defined (adverse) effect, so accurate probabilities are impossible to assess without the use of a rigorous statistical framework.

Risk assessments are structured in tiers and thus a blend of qualitative and quantitative approaches often are employed to produce the final product. As the quality of data employed generally becomes more important as one moves from the scoping to the screening and ultimately to the decision making stages of risk assessments, so too does the role of statistics as the statistical approaches are determined by both the quality and quantity of data as well as the assessment situation (e.g., accident, planned, prospective, retrospective) and objectives. In general, the tolerance for Type I and Type II errors evolves over the course of development of a risk assessment and the statistical stringency increases as one moves toward the decision making stage. Regardless, even during the earliest planning and problem formulation stages of risk assessment development, the use of a robust statistical framework can help determine specifically what information is needed to produce the assessment and what the quality of those data needs to be.

When performing a risk assessment, the role and contributions of statistics to the defensibility of the final product are evident. For example, in the planning and problem formulation stage of risk assessment statistical methods can help in determining the appropriate sampling regime needed to adequately address the questions of interest and help one identify those parameters with a high degree of uncertainty where additional experimental or observational resources should be dedicated. Statistical inference can be used to assess the quality of data as well as to quantify the confidence and uncertainty of the results. Statistical approaches can be used to quantify natural variability, set baselines, and identify thresholds that are relevant to the risk assessment process. The use of a robust statistical framework can help one to explain complex interactions, deal with confounding factors, identify constraining parameters within the ecological system and help to prioritize those interactions that are most influential in determining risk. Finally, appropriate statistical methods can directly inform decision making by quantifying the probability of adverse outcomes, exploring outcomes from differing scenarios and extrapolating probability of risk from one level of biological organization to higher or lower levels with a greater degree of certainty than would be the case for weight of evidence approaches.

3.3.3. Which other methods are most likely to produce data that are both defensible and of utility for risk assessment of radionuclides at the ecosystem level?

The group agreed that a wide range of methodological approaches can be used to produce high quality data that are useful for statistical inference, modelling, and risk assessment. Studies employing experimental manipulations performed in microcosm, mesocosm, and natural field conditions, particularly when planned with insight in a coordinated way and used iteratively to inform each other, have great potential to produce data which are defensible, appropriate for statistical inferences, and useful for construction of quantitative models to inform risk assessment. Below we discuss aspects of modelling, statistical inference and empirical data collection in the laboratory and field that the group felt were critical for the construction of defensible, reliable risk assessments.

3.3.3.1. Conceptual Models

If data are to be collected with a specific risk assessment in mind, the planning and problem formulation stage should start with an agreed conceptual model, based as much as possible on sound scientific knowledge that will guide the design of the study plan, including clearly defined measurement endpoints and explicit statements of data quality objectives. Such conceptual models are best informed by data from multiple empirical levels – microcosm, mesocosm and field studies, particularly of a controlled manipulative type. Field observations and modelling can be used to identify patterns, processes, and uncertainties that need further investigation. Well-constructed experiments (e.g. across gradients of stress) can provide information about mechanisms and information for building conceptual and computational models. Modelling can also be used for constructing hypotheses that can then be tested through lab and field studies (Sazykina and Kryshev 2016; Alonzo et al 2016), as well as prioritizing lab and field work through identifying the relative importance of ecosystem components and processes. Insightful planning is needed to prioritize the sequence of approaches and experiments.

3.3.3.2. Statistical Inference

Ecological risk assessment decisions are often made using an expert opinion approach employing simple rule-based weight of evidence perspectives that lack robust, repeatable or quantitatively defensible foundations. Alternatively, quantitative statistical methods are powerful tools that can provide defensible arguments for decision making in ecological risk assessment, and the move away from weight of evidence to quantitative statistical approaches in risk assessment would have significant benefits. For example, a move to quantitative statistical inference could convert a ‘comfortable’ approach to a ‘comfortable quantitative approach’ (e.g. Bayesian Belief Networks) while utilizing what is known within the context of a robust statistical framework. Use of quantitative statistical approaches also allows us to balance Type I and Type II errors to efficiently incorporate new information at different stages of the decision making process (adaptive inference) and helps to explicitly recognize and incorporate underlying variance to help rationalize field data collection and study design. Finally, the use of quantitative statistical frameworks can improve the construction of ecological risk assessments by integrating causal inference, allowing us to combine evidence from multiple sources simultaneously, objectively benchmark data quality and data gaps and ultimately provide defensible support for later decision making.

3.3.3.3. Empirical Data From Laboratory Experiments

Laboratory approaches may differ depending on whether a risk assessment is prospective or retrospective. In retrospective cases, prior knowledge of the ecosystem (and contaminants, with likely exposure routes) should be used for experimental design and exposures can be done with samples (e.g. water, sediment, soils, organisms, etc.) collected from field sites, for increased realism. A gradient approach is strongly recommended. With prospective risk assessments, the fundamental behavior of contaminants should be taken into account because we may not know what actual environmental conditions are occurring. Experiments should be done in such a way that responses to contaminants at the individual level can be easily measured and used to model responses at higher levels of biological organization (e.g., population level). Whether retrospective or prospective, a basic understanding of the ecosystem (geochemistry, ecology, hydrology, etc.) is desirable to produce a conceptual model before lab experiments are initiated. If actual data are not available to construct such a model, knowledge from ‘similar’ systems should be used. Experiments should not just focus on contaminant behavior, but also ecological endpoints that may have been identified as relevant from the conceptual model. Carefully designed multispecies microcosm and mesocosm studies may be appropriate methodological approaches to successful, controlled laboratory experiments.

3.3.3.4. Empirical Data From Field Experiments

Proper experimental and sampling design is essential prior to initiation of field studies at the ecosystem scale. A coarse- scale, landscape perspective can be useful as a starting point for field-based studies, being refined to investigate higher or lower levels of biological organization as required. Careful consideration should be taken so that data collection is informed by and links to completed or ongoing in situ experiments as well as to results from microcosm and mesocosm studies which may inform the field research. To be defensible, useful, and repeatable, field methods and measured endpoints must be practical and reflect reality to the greatest extent possible. Endpoints measured should be ecosystem relevant (i.e., not solely focused at the individual or population level). Attractive ecosystem relevant endpoints might include: those with an emphasis on community structure, functional groups and ecosystem processes and services; those scalable to different species, populations and areas; those which include repeated measurements over time to capture temporal dynamics and those which are holistic (e.g. include ecological and abiotic measurements in addition to contamination levels). More attention needs to be paid to improving dose quantification at its variability at different spatial scales.

4. SUMMARY DISCUSSION

Following the focused workshop sessions, a final discussion aimed to generate consensus statements agreed by all the participants. These are produced below (*in italics*) and discussed:

4.1. Overall Consensus for Question 1

While still evolving in many respects[1]*, ecosystem science has matured to the point where there are well supported theoretical constructs which allow us to conceptualize the roles, structure and functions of ecosystems in sustaining life. As such, ecosystem science is, and will be, paramount to moving the paradigm of risk assessment beyond organismal toxicology to also include ecological risk assessments which utilize ecosystem-level metrics.*

4.2. Overall Consensus for Question 2

The same ecosystem endpoints used for other contaminants could be used to measure ecological risk from radiological exposures. However, group members stressed that gaps in knowledge still limit the use of ecosystem endpoints in radiation risk assessments despite the fact that they are acknowledged to be more relevant. Radioecology could make more advances merely by going beyond its current approach of determining dose to exposed individuals. A prudent approach could improve risk assessments by incorporating more realistic spatial, temporal, and dosimetric information within risk assessment models and by promoting research necessary to better understand causal linkages across the various levels of biological organization within ecosystems.

[1] Essentially because a unique vision over the ecosystem concept is still debated (landscape theory, thermodynamics, cybernetics and complex systems dynamics/stability)

4.3. Overall Consensus for Question 3

Statistical frameworks and conceptual models are essential as a way to direct ecological risk assessments of radionuclides. They give confidence in decision making for complex processes through causal inference, combining evidence from multiple sources and quantifying probabilities of effects. The type and scope of the situation being addressed dictates the choice among statistical approaches.

5. CONCLUSION

The workshop participants represented a large global community of specialists dealing with a wide array of environmental problems and representing a variety of scientific perspectives. Even with this diversity, there was broad agreement on the need to integrate more ecosystem science into radioecology in particular, but also into risk assessments in general for all kind of stressors. The dramatic on-going decline of the planetary biodiversity (Grime 2002; Ceballos et al. 2017; Hallmann et al. 2017; Ripple et al. 2017; Bélanger and Pilling 2019; Bongaarts 2019) provides a good illustration as to why we should question the methodologies we currently use to assess and predict ecological risks. Such declines force us to acknowledge that our current methods for ecological risk assessment have not allowed us to adequately protect species, nor have they allowed us to appropriately assess risk to ecosystem functions and services that we rely upon. Our participants agreed that the theoretical underpinnings of ecosystem science have evolved to allow us to identify those attributes and parameters of ecosystems that are critical, both to sustaining life and to ensuring functional services. Thus, the stage is set to allow the incorporation of more ecosystem level endpoints into risk assessment generally and radioecology specifically. Ecosystem science is paramount to move the paradigm from the anthropocentric view, which currently dominates risk assessment and is essentially based upon organismal (eco)toxicology, to wider ecological understanding of stressor impact and related risk assessment.

A variety of ecosystem attributes and parameters are attractive as endpoints for development of risk assessments associated with radiation exposure, however, more work needs to be done to conceptually and experimentally clarify what dose actually means at the level of the ecosystem and over what spatial and temporal scales such endpoints are expected to respond to radionuclide stressors. For example, biodiversity represents one possible ecosystem-level endpoint of interest that has been recommended herein. However, this is not yet incorporated into risk assessment methods which still basically rest on understanding of effects of stressors on individual organisms or species rather than on the cumulative stress to populations and communities of organisms at higher levels of biological organization, such as the ecosystem. While it is clear that a move to incorporate ecosystem-level endpoints into risk assessments for radionuclide exposure is attractive and likely more realistic than current approaches, it also is evident that specifically targeted research focused on tying radiation dose to these endpoints in a quantitative, repeatable manner is needed to move forward.

Ultimately, the incorporation of ecosystem science into risk assessment for any stressor will rely on the use of robust, defensible, and repeatable statistical methods at each tier of development within the risk assessment process. The use of well-designed statistical approaches throughout the development of risk assessments can help to overcome the uncertainty inherent to ecological data and provide strong inference for enhancement of our understanding of how stressors and endpoints interact over varying spatial and temporal scales within ecosystems. Weight of evidence approaches to risk assessment are no longer sufficient to address the demand by the public for reliable information on how they and the environments that they live in are threatened by the presence of contaminants.

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GLOSSARY 1.

Ecosystem: A dynamic complex of plant, animal and micro-organism communities (the biocenose) and their non-living environment (the biotope) interacting as a functional unit that forms a stable self-supporting system (http://glossary.eea.europa.eu/).

Ecosystem functions: Ecosystem functions are natural processes or characteristic exchanges of matter and energy that take place in the various animal and plant communities of the different biomes of the world. Primarily, these are exchanges of energy and nutrients in the food chain which are vital to the sustenance of plant and animal life on the planet as well as the decomposition of organic matter and production of biomass made possible by photosynthesis. Life support and general ecosystem services are depending on various ecosystem functions.

Ecosystem structure: The structure of an ecosystem is basically a description of the organisms (biotic component) and physico-chemical features of the corresponding environment (abiotic component). The abiotic component of ecosystems includes basic inorganic elements and compounds, such as soil, water, oxygen, calcium carbonates, phosphates and a variety of organic compounds (by-products of organic activities or death). It also includes such physical factors and ingredients as moisture, wind currents and solar radiation. Radiant energy of sun is the only significant energy source for most ecosystems. The biotic component includes producers (autotrophic components), consumers and decomposers (heterotrophic components or reducers and transformers) and the species richness which they encompass, called biodiversity.

Ecosystem vulnerability: The potential of an ecosystem to modulate its response to stressors over time and space, where that potential is determined by characteristics of an ecosystem that include many levels of organization. It is an estimate of the inability of an ecosystem to tolerate stressors over time and space (Williams and Kapustka 2000).

Ecological risk assessment: Process for analyzing and evaluating the possibility of adverse ecological effects caused by environmental pollutants and stressors.

Ecosystem services: The benefits people obtain from ecosystems. These include provisioning services such as food and water; regulating services such as flood and disease control; cultural services such as spiritual, recreational and cultural benefits; and supporting services such as nutrient cycling that maintain the conditions of life on Earth (from: https://www.greenfacts.org/glossary/def/ecosystem-services.htm)

Assessment endpoint: An assessment endpoint is defined in Guidelines for Ecological Risk Assessment (U.S. EPA, 1998a) as “an explicit expression of the environmental value to be protected, operationally defined as an ecological entity and its attributes”.

Measurement of exposure: Documentation of a stressor’s (e.g., heat pollution, contaminant concentration) presence and quantity.

Measurement endpoint: Effects on assessment endpoints are estimated using measures of effects or measurement endpoints. These are the results of tests or observational studies that are used to estimate the effects on an assessment endpoint. Measures of effect and assessment endpoints may be expressed at the same level of organization (e.g., organism level). However, the same measure of effect may be used, with considerably greater uncertainty, to estimate risks to a population-level assessment endpoint (abundance of fish species) or a community-level endpoint (number of species). (U.S. EPA 2003)

Resilience: Ecological resilience is the capacity of an ecosystem to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks (Walker et al., 2004; Holling, 1973). Disturbances of sufficient magnitude or duration can profoundly affect an ecosystem and may force an ecosystem to reach a threshold beyond which a different regime of processes and structures predominates.

Ecological stability: An ecosystem is said to possess ecological stability (or equilibrium) if it does not experience unexpected large changes in its characteristics across time, or if it is capable of returning to its equilibrium state after a perturbation (a capacity known as resilience) (Levin et al., 2012). The concept is however much debated arguing that although the characteristics of any ecological system are susceptible to changes, during a defined period of time, some remain constant, oscillate, reach a fixed point or present other type of behaviour that can be described as stable (Lewontin, 1969).

Keystone species: A keystone species is a species that has a disproportionately large effect on its environment relative to its abundance (Paine, 1995). Such species are described as playing a critical role in maintaining the structure of an ecological community, affecting many other organisms in an ecosystem and helping to determine the types and numbers of various other species in the community.

Indicator species: An indicator species is any biological species that defines a trait or characteristic of the environment. For an example, a species may delineate an ecoregion or indicate an environmental condition such as a disease outbreak, pollution, species competition or climate change. Indicator species can be among the most sensitive species in a region, and sometimes act as an early warning to monitoring biologists (Farr, 200).

Sentinel species: Some indicator species are also known as sentinel species, i.e. species which are ideal for biomonitoring. Organisms such as oysters, clams, and cockles have been extensively used as biomonitors in marine and estuarine environments.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Table 1. Names and affiliations of participants in workshop entitled Integrating Ecosystem Research into Radioecology in the Nuclear Age held in Aiken S.C. on October 3rd - 5th, of 2016.

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Table 2. Presenters and presentation titles for talks given on day 1 of the workshop entitled Integrating Ecosystem Research into Radioecology in the Nuclear Age held in Aiken S.C. on October 3rd - 5th, of 2016.

Presenter	Presentation Title
Tom Hinton	On the Evolution of Radioecology--And Why We Lost Ecology Along the Way
Clare Bradshaw	Challenges of Integrating Ecosystem Science into Radioecology
François Bréchignac	More Ecology into Radioecology! Overview of the 2015 Consensus Symposium Recommendations
Ken Ishida	Overview of Radioecology Studies at Fukushima
Mike Wood	Recent Ecological Impact Studies in Chernobyl
Evgeny Pryakhin	Indirect Ecology Effects in Radioactively-Contaminated Freshwater Ecosystems
Larry Barnthouse	Challenges of Ecological Risk Assessment for Chemicals
Theresa Mathews	Strategies for Integrating Ecosystem Science into Ecotoxicology
Larry Kapustka	Challenges of Incorporating Ecosystem Level Endpoints into Radiation Protection Programs
Carmel Mothersill	Challenges to Scaling up from the Lab to the Mesocosm and Beyond in Radioecology
Bernard Clément	Coupling Microcosm Experiments to Modelling in Order to Understand Ecological Impacts of Stressors
Ulrik Kautsky	Implementing Ecosystems Models into Radioecology
Bill McShae	Measuring Ecosystem Indicators to Support Ecological Risk Assessment
Mike Newman	The Challenges of Statistical Inference for Ecological Risk Assessments

Graphical abstract

Highlights

- Ecosystem endpoints can be useful for radiological risk assessment
- Ecosystem metrics provide a holistic assessment of ecosystem condition
- Statistical rigor and conceptual modelling are critical to radiological risk assessment